STUDIES WITH RADIOACTIVE PHOSPHORUS IN SOILS OF THE WESTERN STATES, 1950-53

By the Publications Committee, Phosphorus Work Group of The Western Soils Research Committee in cooperation with State Agricultural Experiment Stations and the Soil and Water Conservation Research Division, Agricultural Research Service.

UNITED STATES DEPARTMENT OF AGRICULTURE

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FOREWORD

The Western Soils Research Committee was organized in 1948 by memorandum of understanding between the States of the Western Land-Grant College Region and the Office of Experiment Stations and the Agricultural Research Service of the United States Department of Agriculture. The Committee was directed to consider the regional aspects of soils research and to advise the Land-Grant College Association and the United States Department of Agriculture on soil, fertilizer, and irrigation research problems. One of the subcommittees appointed by the Western Soils Research Committee, through which the Committee carries on its work, is the Phosphorus subcommittee. At its annual work conference held in Logan, Utah, December 7–8, 1953, the subcommittee appointed a publications committee to assemble, prepare for publication, and proceed to publish the papers presented at the Western Regional Phosphorus Work Conferences during the years 1950–53, inclusive. This report is the result of the work of the publications committee.

C. H. WADLEIGH, *Director*
Soil and Water Conservation Research Division
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PREFACE

This publication is based on reports presented at the Western Regional Phosphorus Work Conference during the years 1950–53. The reports are the result of cooperative investigations of the California, Idaho, Montana, Oregon, Utah, and Washington Agricultural Experiment Stations and the Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture. Experimental data in the reports were contributed by: B. A. Krantz and A. J. MacKenzie, Brawley, Calif.; J. V. Jordon, Moscow, Idaho; W. E. Larson and W. B. Johnston, Bozeman, Mont.; A. S. Hunter and J. A. Yungen, Corvallis, Oreg.; J. L. Haddock, H. B. Peterson, R. L. Smith, and R. F. Nielson, Logan, Utah; and C. O. Stanberry, R. L. Hausenbuiller, W. H. Weaver, W. J. Clore, and W. O. Pruitt, Prosser, Wash.

Attendance of contributors and others from the Western Agricultural Experiment Stations was made possible by assistance from the Industry Phosphate Research Committee, V. Sanchelli, Chairman.

The Publications Committee decided to publish a summary of these reports in one publication. In order to make the summarized data as useful as possible, the Committee asked H. B. Peterson, Head, Department of Agronomy, Utah State Agricultural College, to prepare a discussion on the phosphate status and problems in western soils, and C. O. Stanberry, Soil and Water Conservation Research Division, U. S. Department of Agriculture, Yuma, Ariz., to prepare a discussion on principles established by previous experimentation. These, as well as discussions and recommendations that appear justified from the data presented, are included to supplement the compilation of data.

The Committee has attempted to credit States and individuals who sponsored and presented data accumulated at the several locations in the Western States.

The Committee wishes to acknowledge the assistance of personnel of the Fertilizer Investigations Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, in preparing and supplying P^{32}-tagged fertilizers to the various locations. The contributions of W. L. Hill, G. A. Wieczorek, A. V. Breen, L. E. Gross, and M. E. Jefferson are especially appreciated.

Publications Committee:
J. L. HADDOCK, Chairman,
R. L. HAUSENBUILLER,
C. O. STANBERRY.

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Studies With Radioactive Phosphorus in Soils of the Western States, 1950-53

By the Publications Committee, Phosphorus Work Group of the Western Soils Research Committee in cooperation with the California, Idaho, Montana, Oregon, Utah, and Washington Agricultural Experiment Stations and the Soil and Water Conservation Research Division, Agricultural Research Service, United States Department of Agriculture

THE PHOSPHATE STATUS AND PROBLEMS OF WESTERN SOILS

During the period 1934–39, average phosphate fertilizer consumption in the 11 Western States amounted to about 11,000 tons of phosphorus per year. By 1953, consumption had increased to about 63,000 tons of P (*28*).[1] During much of this period of expanding usage the demand exceeded the supply. Since 1950 the rate of consumption has increased slightly, but production facilities have continued to expand so that the production potential currently exceeds the demand.

When soils were first placed under cultivation, their P content was related to parent materials and soil-forming processes. During the time soils have been under cultivation their phosphate status has changed. In some soils the P content has been reduced by cropping; in other soils it has been increased through the use of farm manures and fertilizers. As a result of these differences in cropping and fertilizer practices, phosphate response by crops can no longer be directly related to specific soil series and types.

The average annual rate of application of phosphate in the Western States is low (*7*), but for such crops as sugar beets, potatoes, and vegetables it is relatively high. Consequently, many acres of land may be receiving more than adequate amounts of fertilizer whereas others are inadequately supplied. This suggests a need for an overall expansion of use, as well as an increase in efficiency of use, of phosphate fertilizers. This variable condition points also to the need for a standardized soil test for the appraisal of the P status of cultivated fields. On further evaluation, the sodium bicarbonate test proposed by Olsen and associates (*22*) may be found to fulfill this need.

Certain crops respond to phosphorus more readily than others. This fact, together with the carryover effect of P, suggests that it is practical to fertilize fields on which crops are grown in a rotation with enough P to satisfy all crop needs for several years. It is necessary

[1] Italic numbers in parentheses refer to Literature Cited, p. 31.

before the initiation of such a practice to determine the optimum rate and timing of application in the rotation.

Results from many recent studies indicate no general advantages from placing P fertilizers in bands in the soils of the West. There are exceptions with some row crops, where moisture conditions in the root zone and the P status of the soil are such that the fertilizer is used most effectively when it is placed in bands. Usually, however, this condition exists in soils extremely deficient in P and where moisture conditions are most favorable in the zone where the fertilizer is placed.

The evidence seems to indicate that it is not practical to try to obtain maximum utilization of the P each year of application by placement of small amounts of fertilizer. Because of carryover effects, it seems more desirable to maintain a fairly high level of fertility and to incorporate fertilizer with the soil of the plow layer.

Fundamental studies of reactions of P in soils are being conducted at several experiment stations, and at the Phosphorus Laboratory maintained by the Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, in cooperation with the Colorado Agricultural Experiment Station at Fort Collins, Colo. Such studies should be continued. The findings will serve as a basis for a better understanding of results thus far obtained from field trials, and for the solution of recognized but presently unsolved problems.

PRINCIPLES ESTABLISHED BY PREVIOUS EXPERIMENTATION

Most of the phosphorus in the earth's crust is in one mineral family, the apatite group, usually containing calcium and fluorine. Mineralogical studies of soils reveal that the concentration of P in soil particles of various sizes often increases with decreasing particle size (*6*). In highly weathered soils the sand fractions are considered to be composed chiefly of primary minerals. As the particle size decreases and approaches molecular and ionic limits, there is recrystallization of P compounds into secondary minerals (iron, aluminum, and calcium phosphates) or adsorption on surfaces of clays. Many of the western soils now under irrigation have not undergone intensive weathering, which possibly indicates that the indigenous P is present in primary minerals, chiefly apatitic.

In almost all of the inorganic fertilizers added to the soil, P is either in the orthophosphate form or is hydrolyzed to that form after being added to the soil. When the P in fertilizer comes into intimate contact with the soil it usually undergoes alteration. Such changes are affected by the type of fertilizer material itself, moisture content of the soil, nature and amount of clay present, presence of calcium salts, pH, and the biological activity in the soil. Fertilizer materials with a high degree of water solubility are affected most rapidly.

Most of the irrigated soils of the Western States are neutral or alkaline. The formation of aluminum and iron phosphates, so important in acid soils, appears of minor importance, although McGeorge and Breazeale (*19*) imply that precipitation in difficultly available forms may occur in calcareous soils. Truog (*31*) indicates that 10 to 25 percent of the P often exists as nonapatitic calcium phosphate in neutral soils. This is a satisfactory condition, as crops can obtain ample P from this form for good growth.

Work on calcareous soils in Arizona (*12*) and in Colorado [2] demonstrated that from one-fourth to one-third of the total P may be present in organic combinations.

Investigations by Olsen (*21*) indicate that P, when added to calcareous soils, forms a monolayer on the surface of $CaCO_3$ particles and other surfaces containing calcium. This surface-adsorbed P may be removed by plants for their use. Olsen demonstrated that there is good correlation between the amount of surface P and plant-available P. When soluble P fertilizers are added to soils a precipitation occurs, probably as dicalcium phosphate. This happens when P and Ca concentrations in solution exceed critical values dependent on the solubility product of dicalcium phosphate. On standing, the precipitate becomes richer in calcium and probably eventually forms true apatites (*2*). When not used by plants from the soil solution the ultimate fate of most supplemental P added to highly calcareous soil appears to be the formation of hydroxyapatite or apatitic minerals. Apatites will supply the plant with only a part of the needed P, some plant species feeding from them more effectively than others.

Phosphate may be adsorbed on clay lattices in a difficultly available form (*20*). This effect, however, is most pronounced in acid soils and may be of limited importance in calcareous soils.

In neutral or alkaline soils containing appreciable calcium, several P compounds may be important for plant feeding: Monocalcium phosphate in neutral soils for some time after fertilizer application; surface-adsorbed phosphates; P in organic combination; dicalcium phosphate; and apatite-like minerals. Water-soluble P in the soil is in equilibrium with the solid phase. Although the amount of P available at any one time may be small (less than 1 p. p. m. in the soil solution), the plant can absorb this even though the low concentration in plant tissue may be a thousand times greater than in the soil solution. Plants absorb P as $H_2PO_4^-$ and possibly as $H\,PO_4^=$ ions. The rate of replenishment in the soil solution depends on the nature, quantity, and surface area of the P source. Equilibrium is reestablished rapidly in most soils.

Additions of acidic fertilizers, such as ammonium sulfate, may increase the availability of P to plants. The plant itself may affect the solubility of P from basic calcium phosphates by feeding on and removing calcium from the molecule, or by bonding of Ca on the plant root colloid (*5*). Plant roots and micro-organisms give off acidic compounds that probably increase the availability of P in the soil. The decomposition of organic matter itself also frees some P which is absorbed by the plant. Most of the P obtained by the plant appears to go into solution before being absorbed. The ability of certain plant species to feed more effectively than others on rock phosphate, however, suggests that surface contact between the apatite crystal and plant roots as well as other factors may be important (*8*). Some attempts to obtain evidence for solid-phase feeding have been unsuccessful (*3*), but recent work (*16*) suggests that this mode of feeding is possible.

In addition to the importance of area of surface contact (root size and extensiveness of absorbing surface), legumes generally are more effective than grasses in absorbing P from rock phosphate. There are

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[2] Crab, B. W., organic phosphorus in calcareous colorado soils. 1952. Unpublished master's thesis. Copy on file at Colorado State University, Fort Collins, Colo.

also differences in species with respect to adsorption of P from basic calcium phosphates. Root excretion, elemental balance hypotheses, microbial interactions, or the magnitude of root-cation exchange capacity may be involved (*5, 8*).

Plants growing in soils fertilized with P will contain P from both soil and fertilizer. The relative amount of the nutrient absorbed by the plant from each of these two sources is assumed to be directly proportional to the available supply from each, i. e.:

$$\frac{\text{P available in soil}}{\text{P available in fertilizer}} = \frac{\text{P derived from soil}}{\text{P derived from fertilizer}}$$

This relationship is analogous to that expected if 10 yellow marbles are mixed thoroughly with 90 green ones of the same size. A random sample would be expected to contain 1 yellow to 9 green marbles.

During the last few years the labeling of P in fertilizer with the radioisotope P^{32} has permitted the simple estimation of the amount of P within the plant derived from the applied fertilizer. If the amount of available P applied in the fertilizer and the specific activity (ratio of $P^{32}/P^{31}+P^{32}$) of the P in the fertilizer and in the plant are known, it is possible to determine the available P in the soil. Since all of the P comes from either soil or fertilizer the following usable equation may be derived (*10, 14*):

$$A=B\left(\frac{Sf}{SP}-1\right)$$

where A=amount of P available in the soil for a given crop and season,
B=amount of available P applied in fertilizer,
Sf=specific activity of P in the fertilizer,
SP=specific activity of P in the plant.

In the formula, all P in the added fertilizer is considered available to the plant.

Under general field conditions reduction in "B" (availability of the added P) through chemical fixation or positional inaccessibility to plant roots because of insufficient moisture may alter the "A" value greatly. This results in less P from fertilizer entering the plant. The calculated "A" values may be unreasonably high if reduction in availability of P in fertilizer occurs. And thus a literal interpretation of calculated "A" values is not always permissible. However, valid comparisons are possible by holding location, soil, crop, and climate constant and evaluating differences among various treatments.

If the residual effects from initial applications of different phosphates are estimated over a period of several years, "A" values may not be compared among years because of chemical and physical changes in availability and accessibility affecting "B" for the current tagged application. A fluctuating value for "B" among years, however, should vary the "A" value for indigenous (or native) P and residual P proportionally. Therefore, the ratio of "A indigenous" to "A residual" (Ai/Ar or Ar/Ai) is more acceptable for comparing data between different years.

Numerous fertilizer studies using radioisotopes have resulted in information supplemental to yield response and total nutrient uptake. The sensitivity of this tool permits an evaluation of nutrient sources and method of application, even though crop yields or total nutrient uptake may be unaffected measurably. Also, the availability of

the nutrient to the plant is determined directly, avoiding or permitting an evaluation of confounding interactions (*9*).

Fertilizers tagged with radioisotopes have been utilized to appraise the immediate and residual value of different fertilizer materials; method and position of placement; availability; nutrient uptake with time; total absorption of P by various plants; root elongation; lateral and vertical root zone of the plant; volume of soil involved; root activity; indigenous nutrient supply in soil; movement of fertilizer; particle size of fertilizer; mechanism of nutrient fixation; and the effect of moisture, tillage, and physical properties of soil on the uptake of fertilizer.

METHODS AND MATERIALS

The data presented here were obtained from experiments by investigators in six Western States (California, Idaho, Montana, Oregon, Utah, and Washington). An attempt has been made to (1) give a minimum of detail describing each experiment, (2) present essential data in table form, (3) interpret and explain the data from various sources, and (4) draw conclusions consistent with the data. References are made to other publications to explain and supplement observations reported or to correlate them with phosphate studies reported elsewhere.

The experimental results are treated in three sections: I, Effect of source and placement of phosphate fertilizer on its availability; II, Effect of soil-moisture condition on the availability of phosphorus; and III, The measurement of residual phosphorus, phosphorus uptake by plants, and the effect of nitrogen fertilizer on phosphorus utilization.

In most of the experiments reported herein radioactive phosphorus (P^{32}) was used to tag the P in the applied fertilizer.

EXPERIMENTAL RESULTS AND DISCUSSION

I. EFFECT OF SOURCE AND PLACEMENT OF PHOSPHATE FERTILIZER ON ITS AVAILABILITY

In this section 10 experiments designed to study the effect of various phosphate fertilizers and their placement in the soil on yield and chemical composition of crops are discussed and summarized. Five experiments involve alfalfa (one is a greenhouse study); 2 experiments are with sugar beets; and 1 each is with beans, potatoes, and wheat.

Alfalfa

Superphosphate (SP) and calcium metaphosphate (Ca meta) were broadcast and drilled in bands at the rate of 33 and 66 pounds of P per acre in Millville loam at Logan, Utah, April 7, 1950. This soil has a $CaCO_3$ content of 17 percent, a pH of 7.7, and approximately 2 p. p. m. of CO_2-soluble P. The broadcast fertilizer was disked 3 inches into the soil and the banded fertilizer was placed 5 inches deep in rows 14 inches apart. Ranger alfalfa was drilled in rows 14 inches apart a week after the fertilizer was applied. Plant samples and yields were obtained at the early bloom stage for two cuttings. Differences among the treatments were not statistically significant, although the P from fertilizer in the plant tended to be greater for SP than for Ca meta. Similarly, there was a tendency toward greater recovery of P from broadcast than from banded fertilizer.

In 1951, in a similar experiment at Logan on the same soil, SP and

—40 mesh Ca meta were applied at the rate of 33 pounds of P per acre, on April 13, on a 1-year-old stand of Ranger alfalfa. The banded fertilizer was placed 4 inches deep in rows 12 inches apart. The broadcast application was incorporated into the soil by harrowing in both directions. Plant samples and data on yields were obtained for three cuttings taken at the early bloom stage.

As seen in table 1, yields and P uptake per acre were higher for fertilized alfalfa than for the control, except possibly for Ca meta applied in bands. SP appears to have been utilized more efficiently than Ca meta, as evidenced by the percentage of P derived from the fertilizer, total P uptake per acre, and yields. There was no significant difference between methods of application for either Ca meta or SP.

TABLE 1.—*P derived from fertilizer, total P uptake, and yield of alfalfa, as affected by method of application and source of fertilizer, Logan, Utah, 1951* [1]

Method of application and source of fertilizer [2]	P derived from fertilizer			Total P uptake per acre	Yield of alfalfa per acre
	First cutting	Second cutting	Third cutting		
	Percent	*Percent*	*Percent*	*Pounds*	*Tons*
Control (untreated)	--------	--------	--------	16. 6	3. 27
Broadcast:					
Ca meta	10. 9	21. 3	19. 6	19. 4	3. 54
SP	16. 9	29. 2	21. 0	21. 2	3. 76
Banded:					
Ca meta	7. 1	18. 3	14. 4	18. 1	3. 39
SP	22. 5	26. 5	27. 5	20. 3	3. 66
Least significant difference at 5-percent level	8. 0	N. S.	N. S.	1. 9	. 22

[1] As reported by Nielson.
[2] See text for details on methods of applying fertilizer.

In 1952, at Panguitch, Utah, SP and Ca meta were broadcast and drilled in bands on May 1 at the rate of 33 pounds of P per acre on a 4-year-old stand of alfalfa. SP was also broadcast at the rate of 66 pounds of P per acre. This experiment was conducted on Genola loam, which has a pH of 7.8, 42 percent of $CaCO_3$, and approximately 2 p. p. m. of CO_2-soluble P. The banded fertilizer was placed 4 inches deep in rows 12 inches apart, and the broadcast application was incorporated by harrowing. Yields and plant samples were taken August 2 and September 11. The unavailability of water for a first irrigation resulted in the plots becoming excessively dry, thus delaying harvest of the first cutting about 2 weeks. The Panguitch experiment was continued in 1953 to permit an estimation of the residual effects of phosphorus applied in 1952. Data were obtained for two cuttings. Data for both years are given in table 2.

Table 2.—*Total P content, P derived from fertilizer, and yield of alfalfa, as affected by method of application and source of fertilizer, Panguitch, Utah, 1952 and 1953 (residual)*[1]

Method of application and source of fertilizer[2]	Fertilizer P applied per acre	1952					1953 (residual)		
		Total P in alfalfa		P derived from fertilizer		Yield of alfalfa per acre	Total P in alfalfa		Yield of alfalfa per acre
		First cutting	Second cutting	First cutting	Second cutting		First cutting	Second cutting	
	Pounds	*Percent*	*Percent*	*Percent*	*Percent*	*Tons*	*Percent*	*Percent*	*Tons*
Control (untreated)	----------	0. 170	0. 229	--------	--------	0. 88	0. 145	0. 144	1. 32
Broadcast:									
Ca meta	33	. 202	. 337	39. 0	52. 8	1. 59	. 166	. 248	2. 98
SP	33	. 217	. 339	53. 5	39. 8	1. 98	. 176	. 218	2. 82
SP	66	. 225	. 374	54. 0	48. 3	2. 00	. 188	. 240	2. 95
Banded:									
Ca meta	33	. 202	. 334	54. 2	66. 6	1. 77	. 162	. 185	2. 88
SP	33	. 205	. 335	64. 0	47. 8	1. 81	. 166	. 224	2. 94
Least significant difference at 5-percent level	----------	. 019	. 020	9. 9	9. 2	. 16	. 019	. 046	. 35

[1] As reported by Nielson.
[2] See text for details of methods of applying fertilizer.

During the first year of this 2-year experiment yields and P content of alfalfa were higher for all five fertilizer treatments than for the unfertilized treatment (control). SP applied at the rate of 66 pounds of P per acre increased the P content of the hay and the percentage of P derived from the fertilizer for the second cutting as compared with application at the 33-pound rate but did not increase yields. At the first cutting more P was obtained from SP than from Ca meta, whereas at the second cutting more was obtained from Ca meta. Hay yields showed the two sources of phosphate were equally efficient when applied in bands but SP was superior to Ca meta when broadcast. Method of application did not affect the total percentage of P in the plant, but the percentage of P from fertilizer was higher for both cuttings when the fertilizer was applied in bands. Higher yields were obtained from Ca meta when it was applied in bands than when it was broadcast, whereas the opposite was true for SP.

No significant difference resulted in either the P content or total yield of alfalfa from either the method of application or the source of phosphate in 1953 (residuals). Yields were higher for all fertilizer treatments, however, than for the control.

In 1950, at Prosser, Wash., superphosphate (SP), concentrated superphosphate (CSP), ammonium phosphate (11–48–0), and fused tricalcium phosphate (FTP) were applied in bands 1 inch deep and 6 inches apart at the rate of 35 pounds of P per acre to an 8-year-old stand of Turkistan alfalfa. The soil was Sagemoor fine sandy loam with a pH of 8.0, 3 percent of $CaCO_3$, and 2 p. p. m. of CO_2-soluble P. The N level was equalized through additions of NH_4NO_3 to all plots not receiving 11–48–0. Plant samples were taken May 26, June 16, and August 8 when the alfalfa was in early bloom.

Data (table 3) are characterized by a low utilization of P from fertilizer. This may have been because of a low level of available moisture in the fertilizer-bearing zone of the soil during a major portion of the growing season. Availability of P from FTP was significantly lower than from the other three fertilizers. Yield response was not observed for any of the fertilizers.

TABLE 3.—*Total P content of alfalfa, and P derived from various phosphate fertilizers, Prosser, Wash., 1950* [1]

Source of phosphate [2]	Total P in alfalfa		P derived from fertilizer		
	First cutting	Second cutting	First cutting	Second cutting	Average
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Control (untreated)	0.267	0.148			
CSP	.267	.152	2.5	2.9	2.7
SP	.260	.154	2.1	2.5	2.3
11–48–0	.272	.152	3.1	3.1	3.1
FTP	.256	.140	.6	.6	.6
Least significant difference at 5 percent level	N. S.	N. S.			1.1

[1] As reported by Stanberry.
[2] See text for details on method of application.

TABLE 4.—*Yield and total P content of alfalfa, and P derived from CSP, by method of application, Prosser, Wash., 1951* [1]

Method of application [2]	Total P in alfalfa			P derived from fertilizer		Yield of alfalfa per acre [3]
	First cutting	Second cutting	Third cutting	First cutting	Second cutting	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Tons*
Control (untreated)	0. 188	0. 248	0. 167			6. 7
Broadcast	. 204	. 282	. 196	28. 6	[4] 36. 2	7. 1
Banded:						
½ inch deep	. 204	. 275	. 186	30. 4	31. 5	7. 2
1½ inches deep	. 208	. 265	. 196	32. 0	30. 2	7. 2

[1] As reported by Hausenbuiller and Stanberry.
[2] See text for details on methods of applying fertilizer.
[3] Mean total yield for 3 cuttings.
[4] Significant increase over other methods of application at the 1-percent level.

In 1951, at Prosser, CSP was applied at the rate of 35 pounds of P per acre to 1-year-old alfalfa growing in Sagemoor fine sandy loam. The fertilizer was broadcast and drilled in bands ½ and 1½ inches deep and 6 inches apart. The percentage of P derived from fertilizer was much higher (table 4) than for the experiment conducted at Prosser in 1950. Rates of phosphorus application and characteristics of the soil were similar for both experiments, but the two stands of alfalfa differed considerably in age (8-year-old stand in 1950; 1-year-old stand in 1951). Yields were not affected significantly by differences in methods of applying CSP; all methods resulted in increases over the control in yields and in the P content of the alfalfa. The percentage of P derived from fertilizer was different only in the second cutting when the broadcast application was superior to drilling in bands.

In 1952, at Prosser, a greenhouse trial was designed to measure indirectly the availability of P to alfalfa from (1) CSP, (2) ground alfalfa hay, and (3) FTP, each at a concentration of 17.5 p. p. m. of P (soil-weight basis). Each source, with an additional 17.5 p. p. m. of P^{32}-tagged CSP, was mixed with Sagemoor fine sandy loam and placed in No. 10 cans. A control treatment containing only the tagged P was also included. Ten alfalfa transplants were established in each can and allowed to grow until three clippings had been obtained.

Figure 1, *A*, shows the relative P-supplying values for each of the sources as determined from analyses of plant material obtained at each clipping. The P-supplying values were obtained at each clipping by subtracting the "A" values for the soil alone from those of the soil plus the three sources of P. The loss of P^{32} to the alfalfa between clippings was taken into account in making the calculations for "A" value. This indirect method appears to give reasonable ratings for the relative availability of P from the different phosphate sources.

As indicated in figure 1, *B* and *C*, both total P uptake and yields were higher for ground alfalfa than for CSP. Normally one would con-

clude from this that alfalfa is better than CSP as a source of P. That this may not be the case is evident from figure 1, *A*, where CSP is shown to be capable of supplying available P not only at a higher level than alfalfa residues but also for a longer period of time. There is a possibility, however, that the alfalfa hay may have maintained the tagged CSP in a more available form, accounting for values plotted in figure 1, *A*.

Availability values for fertilizers calculated from indirect measurements are only approximations. The magnitude of error in materials of high availability may be judged from figure 1, *A*, in which two curves for CSP are shown. The lower curve has been adjusted by a method based on the assumption that the radioactive and tracer-free CSP materials were identical in availability. Thus, indigenous P can be calculated as the difference between total P in the plant and twice the radioactive P from fertilizer in the plant. Adjusted availability values for CSP for the first 3 cuttings are 36, 32, and 29 pounds of P. Since 35 pounds of P was actually added, the adjusted values appear more accurate than the values of 39, 42, and 39 for CSP obtained by the method of difference.

The high values obtained by difference are attributed to the increased uptake of native P because of greater growth stimulation by the alfalfa receiving the 70-pound application of P, as compared with the alfalfa receiving the 35-

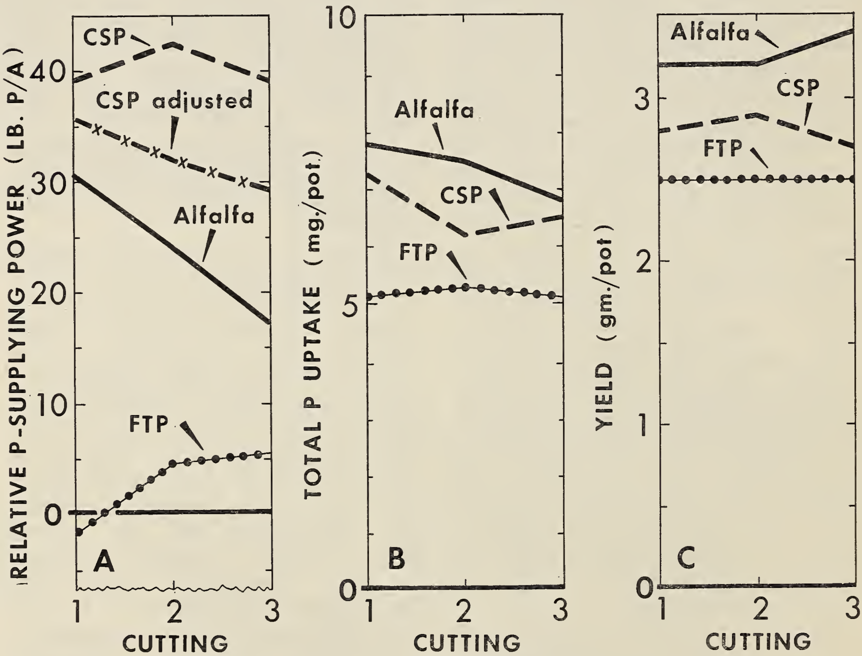

FIGURE 1.—Comparison of CSP, ground alfalfa, and FTP, applied at the rate of 35 pounds of P per 2 million pounds of soil to pot-grown alfalfa (3 cuttings): *A*, relative P-supplying power; *B*, total P uptake; and *C*, yield. (Experiments at Prosser, Wash., in 1952; reported by Hausenbuiller and Weaver.)

pound application (control). This effect has been noted on various occasions in pot studies with Sagemoor soil of low P availability. The error caused by this effect might be reduced if phosphate tracer materials were used at lower rates in making the measurement.

Beans

In 1950, at Prosser, Wash., Red Mexican field beans were planted in Sagemoor fine sandy loam plowed out of alfalfa. NH_4NO_3 was incorporated in the soil during preparation of the seedbed at the rate of 100 pounds per acre. Concentrated superphosphate at the rate of 26 pounds of P per acre was broadcast and incorporated by rototilling before planting and was drilled in bands 2 and 4 inches deep on one or both sides of the row at planting (table 5).

TABLE 5.—*P derived from fertilizer by Red Mexican field beans, as affected by method of application and irrigation treatment, Prosser, Wash., 1950* [1]

Method of application [2]	Irrigation treatment [3]	P derived from fertilizer			
		June 26	July 10	Aug. 4	Sept. 12
		Percent	*Percent*	*Percent*	*Percent*
Banded (both sides of row):					
At seed level	M_1	2.74	2.93	4.22	3.77
2 inches deeper than seed	M_1	4.59	3.80	3.84	4.11
2 inches deeper than seed	M_2	3.86	3.45	4.33	3.98
4 inches deeper than seed	M_1	3.85	4.20	4.43	4.46
4 inches deeper than seed	M_2	4.68	4.84	4.90	4.67
One band 2 inches the other 4 inches deeper than seed	M_1	3.59	4.58	5.02	4.24
Banded (one side of row):					
2 inches deeper than seed	M_1	4.33	4.31	4.03	3.18
Broadcast/rototilled at seed level	M_1	3.11	2.74	3.85	4.86
Least significant difference at 5-percent level		.58	.58	.58	.66

[1] As reported by Stanberry, Pruitt, and Clore.
[2] See text for details.
[3] M_1=Irrigated when moisture tension reached 700 cm. water at 6-inch depth. M_2=Irrigated when moisture tension reached 10 atmospheres at 6-inch depth.

For maximum P uptake from fertilizer the results indicate that: (1) Fertilizer applied in bands should be placed 2 to 4 inches deeper than the seed; (2) there is little difference between the two depths when the soil is kept moist, but considerably more P is obtained from the 4-inch depth in the "dry" treatment (presumably this is because of more favorable moisture conditions at the greater depth); (3) placing one band 2 inches deeper than the seed and one 4 inches deeper is little if any better than placing both bands at either the 2-inch or 4-inch depth; (4) one band is essentially as good as two; and (5) phosphate placed in bands either 2 or 4 inches deeper than the seed is more efficient than the broadcast application when the plants are small, but the broadcast application is equal or superior by the end of the season.

Although this Sagemoor soil had what is considered a low level of available P (3 p. p. m. of CO_2-soluble P), the bean plants were able to obtain more than 95 percent

of their P requirement from the soil. This probably indicates that beans are more efficient than many other plants in obtaining indigenous P. There were no significant differences in bean yields, which indicated sufficient available indigenous P for plant requirements.

Potatoes

Russet Burbank potatoes were grown on Millville loam at Logan, Utah, in 1952 to study the effects of moisture on P uptake from fertilizer applied by different methods. Concentrated superphosphate at the rate of 44 pounds of P per acre was broadcast on the surface and harrowed lightly and was applied in bands at planting 4 inches from the row at depths of 2 and 4 inches, respectively, below the seed. Data are presented later in table 9 and figure 3. Potato-leaf samples were obtained on July 20, August 22, and September 30 to estimate the percentage of P obtained from the fertilizer and the total P content of the leaves.

For the entire season, the method of applying the fertilizer did not affect significantly either the total P content of the leaves or the yield of potatoes, but it did affect significantly the percentage of P obtained from the fertilizer at the first and second sampling dates. There appears to be a trend indicating that the percentage of P obtained from the fertilizer increases as the season progresses when the fertilizer is applied in bands 2 inches deep and when it is broadcast. The percentage of P obtained from fertilizer placed 4 inches deep remained relatively constant. Analyses indicate that the broadcast application at the first sampling date is only 70 percent as effective as the band placed 4 inches deep. By the last sampling date, however, it is 28 percent more effective than the band application.

Sugar Beets

In 1950, at Logan, Utah, sugar beets were planted in Millville loam on May 15. CSP at the rate of 44 pounds of P per acre was broadcast on the surface and was drilled in bands 4 inches from the row and 4 inches deep at planting. Analyses of sugar-beet leaves at the four sampling dates (July 7 and 29, August 19, and September 14) indicate that a higher percentage of P was derived from the band-placed phosphate than from the broadcast phosphate. There were no differences in the total P content of the tops and roots as a result of method of application but the total P content was higher for both methods than for the control. Fertilization did not increase yields.

At Logan, Utah, in 1951, $(NH_4)_2SO_4$ was broadcast at the rate of 80 pounds of N per acre on Millville loam, and sugar beets were planted April 20 in rows 22 inches apart. Immediately after thinning on May 29, CSP at the rate of 44 pounds of P per acre was broadcast and was drilled in bands 3 and 6 inches deep and 4 inches from the row. The three methods of application and a control were subplots in plots maintained at 4 levels of moisture to study the effect of moisture on the availability of phosphorus. Plant samples were obtained July 2 and 31, August 27, and September 16, the final harvest being October 27.

There were no significant differences in yields of tops and roots, possibly in part because of nematode infestation. Selected data are presented in table 6. At the first sampling date, P from the fertilizer placed in bands 6 inches deep was almost 20 times more accessible to the young plants than P from the broadcast application. By the last sampling date, however, almost

twice as much P was obtained from the broadcast application as from bands 6 inches deep. On the dry plots, fertilizer from bands 6 inches deep was more effective than from either the broadcast application or bands 3 inches deep. On the wet plots, however, the broadcast application was the most effective. Apparently there was enough moisture in the surface soil to permit root growth into this area so the broadcast application was available positionally. Considering all 4 moisture levels and all 4 sampling dates, the broadcast application was perhaps more efficient than either band placement.

TABLE 6.—*Yield of sugar beets and P derived from fertilizer, as affected by method of applying CSP, Logan, Utah, 1951* [1]

Method of application [2]	P derived from fertilizer					Yield of roots per acre
	July 2	July 31	Aug 27	Sept 16	Mean	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Tons*
Control (untreated)						10. 3
Broadcast	0. 3	7. 4	15. 2	34. 4	14. 3	10. 7
Banded:						
3 inches deep	2. 9	6. 1	9. 8	20. 9	9. 9	10. 4
6 inches deep	5. 8	8. 4	9. 8	18. 9	10. 7	11. 2
Least significant difference at 5-percent level	1. 0	N. S.	2. 7	4. 4		N. S.

[1] As reported by Haddock.
[2] See text for details on methods of applying fertilizer.

Wheat

In 1952, at Aberdeen, Idaho, Lemhi wheat was grown with different combinations of N and P fertilizers (NH_4NO_3 and CSP) applied at different rates on Declo loam with a pH of 7.8 (table 14). The wheat was planted April 22 in rows 12 inches apart, and the fertilizers were broadcast and applied in bands at planting. Plants were sampled June 6, July 2 and 15, and August 20. Only 2 percent of the applied P was utilized by the wheat. There were no significant differences in P uptake from fertilizer as a result of method of application.

DISCUSSION

Conclusions reported herein are in general agreement with, and supplement summaries of, findings of other investigators who have reported on similar soils (*1, 4, 11, 17, 23, 24, 25, 26, 27, 30*).

Commercial phosphate fertilizers may be listed in four groups based on characteristics affecting method of general use on alkaline or calcareous soils under field conditions.

Fertilizer	*Group*
Superphosphate	I
Concentrated superphosphate.	I
Mono-ammonium phosphate (11–48–0).	I
Phosphoric acid	I
Nitric phosphates with high degree of water solubility (12–32–0).	I or II
Moderately ammoniated concentrated superphosphate.	I or II

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Fertilizer	*Group*
Slightly ammoniated superphosphate.	I or II
Calcium metaphosphate	II
Rhenania or silico phosphate.	II or III
Nitric phosphates with low degree of water solubility (17–22–0).	II or III
Heavily ammoniated concentrated superphosphate.	II or III
Moderate to heavily ammoniated superphosphate.	II, III, or IV
Dicalcium phosphate	III
Fused tricalcium and calcined phosphates.	IV
Colloidal, rock, or tricalcium phosphates.	IV

Fertilizers in group I have a high degree of water solubility, whereas those in group II are partially water-soluble or undergo a chemical reaction that converts them to a water-soluble form (e. g., Ca meta). Phosphorus in the fertilizers in group III exists dominantly as dicalcium phosphate; in those in group IV, it exists in an apatite-like form.

Suitability within each group may vary, depending on the material, particle size, and specific conditions of use. Fertilizers in group IV, however, are unsuitable because their P is relatively unavailable to plants growing in calcareous soils. In studies using P^{32} the percentage of P in the plant derived from the fertilizer often is greatest from fertilizers in group I and least from those in groups II and III. This usually occurs where relative differences in positional availability or extent of P surface are important. For crop yields, however, results indicate that fertilizers in the first three groups are comparable under most conditions, especially if small particle size, thorough mixing in the soil, and favorable moisture conditions are provided. Residual effects are similar also. Water solubility of phosphatic fertilizers in calcareous soils is not a satisfactory single criterion of available P. Plants can feed successfully for P on both water-soluble and dicalcium phosphates.

The important difference between water-soluble phosphates (group I) and those with limited solubility (groups II and III) appears to be in the extent of surface exposed to the solvent action of roots. Phosphate from water-soluble carriers dissolves and then is adsorbed in a monomolecular layer over a large surface (*2*, *21*) or is reprecipitated as minute crystals of dicalcium phosphate. The initial surface area of the particle thus is multiplied many times. Because of the low water solubility of the dicalcium phosphate in groups II and III, there is little increase in surface area exposed to roots, such as occurs in water-soluble forms. Therefore, fine particle size is relatively much more important for the phosphates in groups II and III than for the water-soluble phosphates in group I.

To be utilized, P must be in a suitable chemical form and it must be where it is positionally accessible to plant roots. Method of application and position of the fertilizer are important in relation to the type and development of root system, product of fertilizer reaction with the soil, and particle size. Although P movement is limited in most soils, water-soluble fertilizers may move to a limited extent either in solution or as discrete particles. Fertilizers with little solubility must depend on movement only as particles. This necessitates adequate distribution of fine particles in the feeding zone where roots may maintain contact with a large phosphate surface. Thus, in materials such as dicalcium phosphate, more accessibility to plants will result from fine particles appropriately distributed

than from granules. This is also true for Ca meta immediately after application and to a lesser extent for rhenania or silico phosphates. These materials, however, undergo hydrolysis or other chemical reactions that convert them, at least temporarily, to a water-soluble form, whereupon particle size becomes less important. Their availability increases with time. Broadcasting and plowing under or incorporating them thoroughly leaves P more available to the plant than either applying in bands or broadcasting on the surface. This is particularly true when moisture is inadequate near the soil surface either for the desired chemical reactions or for root growth.

Fertilizer applied in bands in the immediate root zone results in early uptake of P by the plant. Improved efficiency from the broadcast application is attributed to greater contact between fertilizer and feeder roots of the plant. Adequate moisture for development of feeder roots near the soil surface must be maintained for efficient utilization of broadcast phosphate. This can usually be done more satisfactorily in cool than in hot climates.

It cannot be stated categorically that banding, broadcasting, or incorporating fertilizer is the best method of application. Superiority of a given method depends on factors such as type and age of crop, moisture supply, soil fertility, time of application, and P fixation by the soil.

II. EFFECT OF SOIL-MOISTURE CONDITION ON THE AVAILABILITY OF PHOSPHORUS

The studies in this section involve the use of P^{32} in 6 experiments (5 field experiments and 1 greenhouse study) in 4 States (Oregon, Utah, Montana, and Washington). Three of the field experiments were with sugar beets, one was with potatoes, and one was with field beans. Crops were irrigated to provide a range of soil-moisture conditions from wet to dry. Corn was used in the greenhouse study.

The soils in these investigations contained less than 4 p. p. m. of CO_2-soluble P. However, plant growth did not appear to be seriously limited in any of the experiments because of insufficient available P in the soil.

Sugar Beets

In 1950, at Ontario, Oreg., sugar beets were grown at 3 levels of soil moisture on Nampa loam having a pH of 7.0. Fertilizer was placed about 3 inches to the side of the seed and 1½ inches deep at seeding, as follows: 35 pounds of P per acre was applied to all plots; 80 pounds of N per acre was applied to half the plots; the other half received no N. Data in table 7 are means for the two applications of N.

Yields of roots and tops were not significantly different for the three soil-moisture conditions, but there was a marked tendency for each to increase with increasing soil moisture. If it is assumed that soil conditions ranged from wet (M_1) to moderately dry (M_2) to dry (M_3), it appears that the percentage of P absorbed from the applied fertilizer by the sugar-beet plants increased as soil-moisture conditions became less favorable for growth. Apparently, the more favorable the soil-moisture condition for absorption of native P, the less the plant has need for P from fertilizer.

In an experiment at North Logan, Utah, in 1950, sugar beets were grown in Millville loam on plots maintained at 3 levels of moisture. The soil had a pH of 7.9, approximately 50 percent of

TABLE 7.—*Yield and total P content of sugar beets, and P derived from fertilizer, as affected by irrigation treatment, Ontario, Oreg., 1950* [1]

Irrigation treatment [2]	Yield per acre (fresh weight)		Total P content (dry weight)		P derived from fertilizer		Total P uptake per acre
	Roots	Tops	Roots	Tops			
	Tons	*Tons*	*Percent*	*Percent*	*Percent*	*Pounds per acre*	*Pounds*
M_1	19.9	12.3	0.087	0.187	32.9	4.39	13.37
M_2	18.7	8.7	.081	.151	35.3	4.05	11.46
M_3	17.8	8.3	.096	.172	37.7	4.76	12.63
Least significant difference at 5-percent level	N. S.	N. S.	-------	-------	3.8	N. S.	N. S.

[1] As reported by Hunter and Yungen. See text for details on methods of applying fertilizer.

[2] M_1=Moisture tension below 850 cm. water at 8-inch depth throughout season. M_2=Same as M_1 until August 10, then irrigation ceased. M_3=Same as M_1 until July 1, then irrigated when moisture tension reached 15 atmospheres at 8-inch depth.

TABLE 8.—*Yield and total P content of sugar beets, and P obtained from fertilizer, as affected by irrigation treatment, North Logan, Utah, 1950* [1]

Irrigation treatment [2]	Yield per acre (fresh weight)		Total P content (dry weight)		P derived from fertilizer		Soluble P content of petioles[3]	Total P uptake per acre
	Roots	Tops	Roots	Tops				
	Tons	*Tons*	*Percent*	*Percent*	*Pounds per acre*	*Percent*	*P. p. m.*	*Pounds*
M_1	16.9	15.4	0.080	0.170	3.65	25.4	964	14.2
M_2	16.4	16.8	.071	.160	4.14	31.1	839	13.3
M_3	11.7	14.9	.060	.139	2.64	27.5	726	9.7
Least significant difference at 5-percent level	1.9	N. S.	N. S.	.019	-------	5.6	190	1.6

[1] As reported by Haddock. See text for details on methods of applying fertilizer.

[2] M_1=Moisture tension maintained below 250 cm. of water at 6-inch depth throughout the season. M_2=Moisture tension below 3.63 atmospheres at 12-inch depth, as estimated by means of gypsum blocks. M_3=Moisture tension below 6.92 atmospheres at 18-inch depth, as estimated by means of gypsum blocks.

[3] October 21, 1950.

$CaCO_3$ equivalent, and 1 p. p. m. of CO_2-soluble P. All plots received an application of P at the rate of 44 pounds per acre from CSP, either broadcast or placed in bands 4 inches deep and 4 inches to the side of the row. Data in table 8 are means for the two methods of application.

Under the conditions of this experiment, yields of roots were affected significantly by the irrigation treatments. The P content of the roots indicates a tendency for

availability of P to increase as soil moisture increases. Supporting this conclusion are data on the P content of dry tops, total P uptake by the crop, and the soluble P content of petioles.

Although CO_2-soluble P in the soil of these plots was low, the P content of petioles does not indicate a serious deficiency. But the P content was significantly lower in petioles from dry plots (M_3) than from wet plots (M_1). Where serious deficiency exists, the soluble P content of beet petioles usually is less than 600 p. p. m. The soluble P content of petioles from plots M_3 was approaching the critical concentration (726 p. p. m.).

Yield of roots and P content of tops were both significantly lower on plots M_3 than on plots M_1 and M_2, which suggests that P may be limiting under moisture conditions of plots M_3.

P obtained from fertilizer was significantly higher on the moderately dry plots (M_2) than on the wet plots (M_1). This is in agreement with the Oregon data. Although slightly less P from fertilizer was indicated on plots M_3 than on plots M_2, the difference was not significant. The percentage of P from fertilizer obtained by sugar-beet plants tends to be lower on wet soil (M_1) than on moderately dry soil (M_2), even though conditions in the dry soil are less favorable for adsorption of indigenous P.

The major objective of an experiment conducted in 1953 at Huntley, Mont., with sugar beets grown on Pryor silty clay loam, was to determine the effect of soil-moisture condition on rate of root penetration by the beets during early stages of growth. It was concluded that allowing beets to exhaust the available moisture in the surface soil did not stimulate growth.

Two regimes of soil moisture were maintained: (1) Moist (M), irrigated to moisten all dry soil in the root zone when 54 percent of the available moisture had been removed; and (2) dry (D), no irrigations (fig. 2). Ground water was present constantly at about 4 feet below the surface.

The rate of growth and activity of the roots was determined by the method of Hall (*13*). On June 15 to 18, 3 millicuries of dissolved P^{32} was placed around the root system of each plant at depths of 1, 2, and 3 feet. Radioactivity was measured in the field by means of a surveymeter reading of the leaves each week throughout the season. Maximum activity readings were 5 to 8 days earlier on the moist plots than on the dry plots (fig. 2). After the middle of July soils on the dry plots were near the wilting percentage down to the 3-foot depth.

Seasonal variation in concentration of P^{32} in sugar-beet tops, as determined in the field with a survey meter, is shown in figure 2. The data show that the P^{32} content of sugar beets was higher in plants grown on dry soils than in plants grown on moist soils. This was particularly noticeable after July 16. Yields of sugar beets for the moist and dry soils were 22.9 and 20.1 tons per acre, respectively.

Why is it that sugar-beet plants show a higher P uptake from fertilizer placed on dry soil (D) than on moist soil (M)? The data from Oregon (table 7) and from Utah (table 8) show that the sugar-beet plant may obtain a relatively greater proportion of its requirements from applied P where soil conditions are unfavorable for absorption of soil P than where soil conditions are favorable for absorption of soil P. When native P is in limited supply in the greater part of the root zone as a result of low moisture, the plant may be expected to draw on localized concentrations of P from fertilizer to

relieve its needs for P. In this study, liquid phosphoric acid was placed in the vicinity of plant roots at depths of 1, 2, and 3 feet. These islands of highly concentrated phosphorus appear to be drawn on to a relatively greater extent by sugar beets growing in dry soil than by those growing in wet soil. This does not mean that plants obtain more P from dry than from wet soil, but it does mean that in dry soil a greater proportion of total P is obtained from P in fertilizer.

Beans

An experiment with Red Mexican field beans at Prosser, Wash., in 1950, was described earlier (page 11 and table 5). The quantity of available P in the soil is similar to that found in the Oregon and Utah soils.

Under conditions of high soil-moisture tension (M_2 plots), bean plants absorbed significantly greater quantities of P from fertilizer placed 4 inches deep than from fertilizer placed 2 inches deep. This was probably because soil-moisture conditions were slightly more favorable at the greater depth. Where the band of P was placed 2 inches deeper than the seed, the plants absorbed more P from fertilizer on wet plots (M_1) than on dry plots (M_2) when they were small, as indicated in the data for June 26 in table 5. There was no significant difference due to moisture levels for the last three sampling dates. The dry (M_2) treatment, however, was definitely superior for the first two samplings where the fertilizer band was 4 inches deeper than the seed level. Also it was as good as or better than the M_1 treatment for the last two sampling dates.

Potatoes

In 1952, in an experiment at North Logan, Utah, Russet Bur-

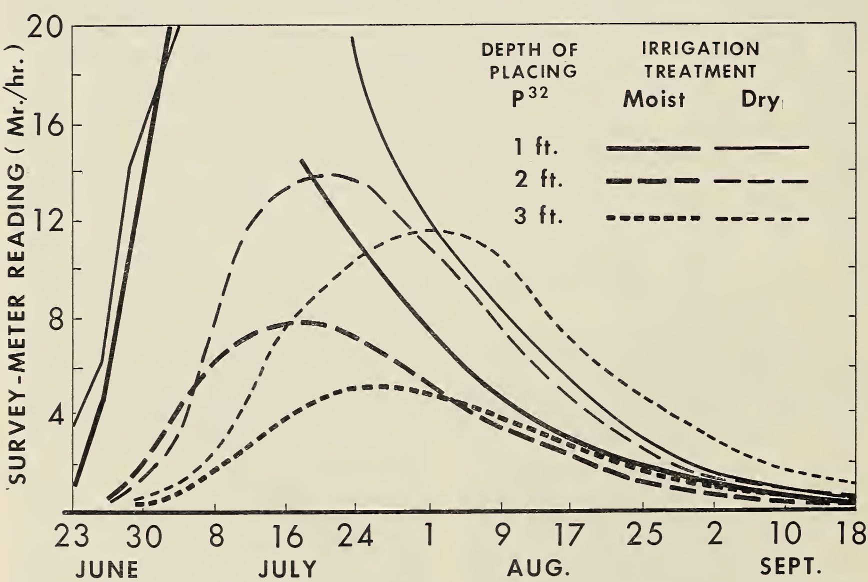

FIGURE 2.—Effect of soil-moisture condition and fertilizer placement on the radioactivity of sugar-beet leaves, as determined by weekly survey-meter readings in the field, Huntley, Mont., 1953. (As reported by Larson and Johnston.)

TABLE 9.—*Yield of potatoes, total P content of leaves, and P obtained from fertilizer, as affected by irrigation treatment, North Logan, Utah, 1952* [1]

Irrigation treatment [2]	Yield per acre [3]	P derived from fertilizer			Total P content of leaves		
		July 30	Aug. 22	Sept. 20	July 30	Aug. 22	Sept. 20
	Bushels	*Percent*	*Percent*	*Percent*	*P. p. m.*	*P. p. m.*	*P. p. m.*
M_1	542	7. 21	8. 09	12. 02	2, 304	2, 152	2, 097
M_2	548	6. 54	8. 55	10. 35	2, 263	1, 684	1, 682
M_3	565	6. 16	3. 67	3. 70	2, 224	1, 853	1, 813
M_4	510	2. 29	5. 29	1. 08	2, 095	1, 873	1, 571
Least significant difference at 5-percent level	N. S.	1. 78	1. 66	4. 00	N. S.	142	117

[1] As reported by Haddock. See text for details on methods of applying fertilizer.
[2] M_1=High moisture, 16 irrigations. M_2=Medium-high moisture, 8 irrigations. M_3=Medium-low moisture, 3 irrigations. M_4=Low moisture, 2 irrigations.
[3] Mean of 3 fertilizer placement plots, and the control (unfertilized).

bank potatoes were grown on calcareous Millville loam at 4 levels of soil moisture. Phosphorus at the rate of 44 pounds of P per acre from CSP was broadcast and was placed in bands 4 inches to the side of the row and either 2 inches or 4 inches below the surface.

Data on yields, P content of potato leaves, and percentage of P obtained from fertilizer were obtained on July 30, August 22, and September 20 (table 9).

The soil-moisture conditions studied apparently had little effect on yields of potatoes. Although there was a tendency for the P content of potato leaves to increase as soil moisture increased, the results were not always consistent, as indicated by the data for the second and third sampling dates (August 22 and September 20).

The percentage of P from fertilizer obtained by the plant was low. More P from fertilizer was obtained by the potatoes grown on wet soil (plots M_1 and M_2) than by the potatoes grown on dry soil (plots M_3 and M_4). This appears to be contradictory to the results with sugar beets (tables 7 and 8 and fig. 1). However, there is no evidence that the potato plants were under stress for P even on the driest plots. Furthermore, a seasonal soil-moisture tension graph shows that soil-moisture tension at the 6-inch depth was greater than 6 atmospheres for most of the season even on the driest plots (M_3 and M_4). Plots M_4 were under greater tension for longer periods than plots M_3. No fertilizer was placed deeper than 4 inches; it is not surprising, therefore, that the percentage of P obtained from the fertilizer was low in plants growing on the dry plots. The applied P was positionally unavailable to plant roots on the dry plots.

The effect of soil moisture on P uptake from applied fertilizer is shown graphically in figure 3. The percentage of P obtained from fertilizer was relatively high on the wet plots (M_1 and M_2) at all sampling dates, regardless of method of application. The percentage of P obtained from fertilizer at the first

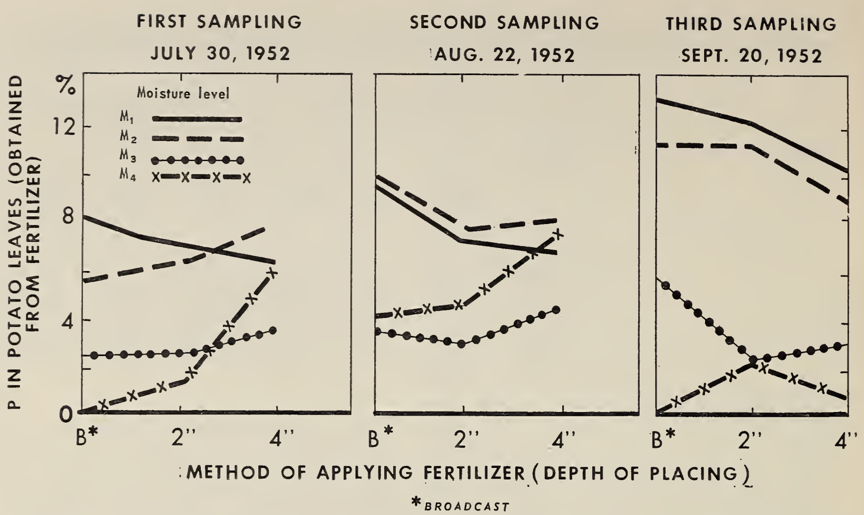

Figure 3.—Percentage of P from fertilizer in potato leaves, as affected by soil-moisture condition and fertilizer placement, North Logan, Utah, 1952. (As reported by Haddock.)

and second sampling dates increased with depth of placement on the dry plots (M_3 and M_4). Depth of placement had little effect on the percentage of P obtained from fertilizer on the wet plots. When soil moisture is high, P from broadcast fertilizer is readily available in the surface soil, but when the surface soil becomes dry for long periods, P from fertilizer placed below the surface is more readily available.

Greenhouse Study with Corn

A greenhouse study, using Nibley clay loam, was conducted at Logan, Utah, in 1952, to determine the effect of various levels of soil moisture on root extension and P uptake by corn. Metal containers were separated into two horizontal sections by a moisture-impermeable membrane constructed according to the suggested design of Hunter and Kelley (*15*). The lower compartments were filled with P^{32}-treated soil moistened to an initial moisture content ranging from 5 to 27 percent (table 10). They received no additional moisture. The upper compartments were filled with untreated soil, supplied with adequate moisture throughout the experiment, and seeded to corn. The plants were harvested after 6 weeks.

The corn roots did not extend into air-dry soil. However, they did penetrate into soil with a moisture tension above 15 atmospheres. Uptake of P^{32} from the lower compartments increased in the order of increasing soil moisture.

The percentage of P derived from fertilizer (table 10) indicates that uptake of P^{32} from the lower compartments was related to the total P uptake from the entire soil mass throughout the containers.

Other trials of a similar nature showed that plants in soils kept moist utilized P more effectively from fertilizer when it was applied near the surface than when it was placed at lower depths. In addition, little P^{32} was taken up from

TABLE 10.—*Effect of level of soil moisture on root extension, P content, and P derived from fertilizer, by corn grown in a greenhouse study, Logan, Utah, 1952* [1]

Moisture level		Root extension [2]	Total P content	P derived from fertilizer	
Initial (percent)	Final (percent)				
		Inches	*P. p. m.*	*P. p. m.*	*Percent*
5 [3]	5	0	1, 660	0	0
12	15	2	1, 890	150	8
16 [4]	16	3	1, 975	265	13
17	15	4	2, 440	975	40
27	22	[5] 6	3, 465	1, 585	46

[1] As reported by Smith and Peterson.
[2] Roots penetrated into the zone having a moisture level as indicated from the zone above having adequate soil moisture.
[3] Air-dry soil.
[4] Equivalent to permanent wilting percentage.
[5] Penetration through entire compartment.

the surface soil if it was allowed to become dry, even though there was sufficient moisture at lower depths.

DISCUSSION

The experiments reported in this section were conducted in the Western States on a variety of soils using different crops to determine the effect of soil moisture on the availability of P. The data show that soil moisture is an important factor among other important ones affecting the availability of P.

The experiments conducted with sugar beets in Oregon, Montana, and Utah indicate that soil P is more readily available as soil moisture increases. However, the percentage of P obtained from fertilizer may depend on the soil-moisture condition with respect to placement of the fertilizer. Where soil P is limited in availability as a result of low moisture, it is probable that P in fertilizer placed in concentrated areas of the root zone is utilized to a greater extent than would be the case if fertilizer were similarly placed in a moist soil where relatively more soil P is available to the plant.

There is evidence that the soil-moisture condition may either favor or hinder extension of plant roots and availability of P. Increasing soil moisture may favor root extension as well as availability of P until aeration sets limitations on root extension. Further increase in soil moisture may limit availability of P only by limiting root activity. On the other hand, decreasing soil moisture not only limits root extension in dry soil but also limits the total quantity of P which can be in solution and available to plants. The percentage of P obtained from fertilizer bears a complex relation to the location of the fertilizer, the distribution of plant roots, the available P content of the soil, soil-moisture condition, and the nature of the plant. When these factors are considered there appears to be harmony in conclusions to be drawn from the data under discussion. The greenhouse study with corn and the field studies with sugar beets, potatoes, and beans bear evidence that

the difficulty in explaining the results of observations is associated with lack of sufficient information about availability of P in soil, availability of nitrogen, soil-moisture condition, plant composition, and other factors.

III. MEASUREMENT OF RESIDUAL P, UPTAKE OF P BY PLANTS, AND EFFECT OF NITROGEN ON UTILIZATION OF P

This section includes reports of 7 experiments from 4 States (Washington, California, Oregon, and Idaho) on the ability of crops to obtain P from currently applied and residual P in fertilizer. Five experiments deal with the effect of nitrogen fertilization on utilization of P from soil and fertilizers. Three of the seven experiments are from greenhouse studies.

MEASUREMENT OF RESIDUAL PHOSPHORUS

A series of plots, established in 1923 at Prosser, Wash., on Sagemoor fine sandy loam, were cropped continually to nonlegumes in rotation. Four untreated plots served as controls. Various fertilizer materials were applied annually to the others. Among the fertilizers applied were N or P alone or in combination. The phosphate status of soils from these plots was studied in greenhouse trials in 1953. The soils were examined to determine the effect of continual application of N on the level of residual P in plots receiving N only and in plots receiving both N and P.

Duplicate trials were established in the greenhouse with surface soil (to a depth of 8 inches) representing the control plots and each fertilizer treatment. Barley was used as the test plant and resin-absorbed P was used as the source of radioactive fertilizer.

In addition to the "A" value, the amount of 0.5M $NaHCO_3$-soluble P was determined (table 11). On both the nonphosphated controls and P plots, annual applications of 150 pounds of N failed to reduce materially the level of residual available P compared to no nitrogen treatment. These results supplement those reported earlier by Stanberry (*29*).

Failure to find differences in residual P as a result of adding N only (N plots) may be because of the relatively complete exhaustion of readily available P in control plots

TABLE 11.—*Residual P ($NaHCO_3$–soluble P and "A" value) in soils from plots cropped continuously in rotation since 1923 and maintained with various fertilizer treatments, Prosser, Wash., 1953* [1]

Fertilizer treatment [2]	Plots	$NaHCO_3$-soluble P [3]	"A" value [3]
	Number	*Pounds*	*Pounds*
Control (untreated)	4	6	22
N plots	4	6	24
P plots	2	82	140
NP plots	2	77	157

[1] As reported by Hausenbuiller and Weaver.
[2] See text for details of methods of applying fertilizer.
[3] Pounds of P per 2 million pounds of soil.

as well as in N plots over the 30-year cropping period. However, where P was added, large applications were made (CSP at the rate of 77 pounds per acre annually for a 20-year period). Of the total of 1,540 pounds added, it is estimated that approximately 1,320 pounds should have remained unused in the plots with added N (NP plots) and at least 1,450 pounds in the plots without N (P plots). It appears probable that differences due to N application were too small to be detected by the methods used.

Perhaps more important is the fact that only about 10 percent of the P added during the 20-year period remained in a form as available as the resin-P used in conducting the experiment. This estimate does not agree with the findings of Olsen (*21*) who estimated that 27 percent of the added P remained available. There probably was some error involved in the Prosser experiment in measuring the high levels of residual P. However, the apparent reduction in the availability of the added P may be the result of a conversion of the CSP to a less available form (*2*).

PHOSPHORUS UPTAKE BY DIFFERENT CROPS

It long has been observed that on a given soil some crops respond to applications of phosphate whereas others do not. Attempts have been made to rank these crops according to their relative needs for P and on their ability to obtain it from a given soil. The total demand for P by the plant, the extent of the plant's root system, and its ability to feed successfully on the indigenous P in the soil are all important factors in determining plant needs for supplemental phosphate (*8*, *31*).

During 1951, five crops (cotton, castor beans, corn, tomatoes, and cantaloups) were grown in the Imperial Valley, California, to determine their relative ability to obtain P from Holtville silty clay soil. At planting time, April 2 to 4, CSP was placed 4 inches to one side and 2 inches deeper than the seed at rates of 0, 17.5, and 35 pounds of P per acre. P applied at the 17.5-pound rate was radioactive. An application of N considered ample was supplied each crop.

Radioactive assays were made on samples of the total aboveground portion of the plants obtained on May 21 to 25 and again on August 3 to 7. Final yields were determined for the various crops at appropriate harvesting times.

Data on yields, P content of the plants, and the percentage of P obtained from the fertilizer are given in table 12. Application of P at different rates caused no significant differences in either yield or composition; therefore, these detailed data are not given.

As expected, significant differences exist among the different crops in both yield and P content. Also, although P uptake from the applied fertilizer was relatively small, there are highly significant differences among the crops. The vegetable crops (tomatoes and cantaloups) absorbed a higher percentage of P from fertilizer than the field crops (corn, cotton, and castor beans). There was no difference, however, among the crops within each of the two groups. The radioactivity of the plant samples obtained on the second sampling date (August 3 to 7) was insufficient to permit reliable readings.

In a similar experiment on a less fertile soil, Fuller (*11*) compared cantaloups and cotton. He also found that considerably more P from the indigenous supply was obtained by cotton than by cantaloups, even though the P uptake from the applied fertilizer was much greater in his experiments.

TABLE 12.—*Yield per acre, total P content, and P derived from applied fertilizers by 5 crops grown in Holtville silty clay, Brawley, Calif., 1951* [1]

Crop	Yield per acre [2]		Total P content [3]		P derived from fertilizer [4]
	May 21–25	Final	May 21–25	Aug. 3–7	May 21–25
	Pounds	*Pounds*	*Percent*	*Percent*	*Percent*
Cotton	188	3, 159	0. 583		0. 41
Castor beans	212	1, 227	. 571	0. 463	1. 28
Corn	422	1, 590	. 426	. 247	1. 66
Tomatoes:					
Vines	58		. 429	. 223	4. 78
Fruit		1, 411		. 460	
Cantaloups:					
Vines	224		. 538	. 288	7. 45
Fruit		1, 799		. 602	
Least significant difference:					
At 5-percent level	48	596	. 108	. 120	3. 09
At 1-percent level	59	821	. 148	. 164	4. 29

[1] As reported by Krantz and MacKenzie. See text for details on methods of applying fertilizer.
[2] May 21–25 sampling: Total dry matter of aboveground portion of plants. Final: Corn, grain at 15.5 percent of moisture; castor beans, air-dry cleaned beans; cotton, seed cotton; cantaloups and tomatoes, 10 percent of fresh weight of fruit.
[3] Both sampling dates: Aboveground portion of plant. Cotton not analyzed in August because of difficulty in grinding lint.
[4] Aboveground portion of plant.

EFFECT OF NITROGEN ON UTILIZATION OF PHOSPHORUS

Applications of nitrogen to most crops in the field normally result in greater removal of P from the soil. This fact has been used as the basis for increased phosphate fertilization in many areas. Little is known, however, concerning the differential effect that applications of N might have on the utilization of native P and P from fertilizer in soils. Radioactive phosphate fertilizer materials have made possible the study of such effects.

Three field experiments involving N variables, conducted during the 1950–53 period, are reported herein. The studies were with sugar beets, wheat, and three wheatgrasses.

Sugar Beets

In a comprehensive study at Ontario, Oreg., in 1950, sugar beets were grown on Nampa loam with various irrigation treatments and levels of N, and a single heavy application of P. The soil had a pH of 7.0 and a low level (3.5 p. p. m.) of CO_2-soluble P. Results of the moisture studies were given earlier (table 7).

Fertilizer was applied as follows: 35 pounds per acre of P^{32}-tagged CSP was applied to all plots; 80 pounds per acre of N as $(NH_4)_2SO_4$ was applied to half the plots; the other half received no N. Data are given in table 13 on percentage of P derived from fertilizer in samples

TABLE 13.—*Yield, total P uptake per acre, and P derived from fertilizer by sugar beets, as affected by applications of N and P fertilizers, Ontario, Oreg., 1950* [1] [2]

Fertilizer treatment [3]	P derived from fertilizer				Total P uptake per acre		Yield of roots per acre
	May 30	June 18	Aug. 1	Sept. 19	Roots	Tops	
	Percent	*Percent*	*Percent*	*Percent*	*Pounds*	*Pounds*	*Tons*
Control (untreated)							12.5
P (35 pounds per acre):							
No N	72.7	78.5	44.9	35.9	7.79	4.68	17.7
N (80 pounds per acre)	76.7	68.3	38.7	34.2	6.56	5.94	19.9
Least significant difference, at 5-percent level	N. S.	N. S.	N. S.	N. S.	1.09	.86	1.8

[1] As reported by Hunter and Yungen.
[2] Mean for 3 moisture treatments.
[3] See text for details of methods of applying fertilizer.

of beet leaves obtained May 30, June 18, August 1, and September 19; total P uptake by roots and tops; and yield per acre. The data are mean values for three levels of soil moisture. There was no moisture-fertilizer interaction.

Application of N reduced the P content of the beet roots from 0.099 to 0.078 percent and of the tops from 0.181 to 0.159 percent. The increase in yields of roots as a result of applying N was insufficient to alter total P uptake appreciably. Considering the increase in yield attributable to P (table 13), this unusual behavior may be the result of the low level of available P in the soil.

Addition of N did not affect materially the ratio of soil P to fertilizer P in plant tops. Apparently, any effects of the added N on P uptake applied about equally to the two sources of P.

Wheat

An experiment to measure the effect of applications of N on P uptake was conducted at Aberdeen, Idaho, in 1952, with Lemhi wheat grown on irrigated Declo loam having a pH of 7.8. NH_4NO_3 was applied to half the plots at the rate of 80 pounds per acre; the other half received no N. CSP was applied at the rate of 0, 17.5, and 35 pounds of P per acre to each treatment of N. N and CSP were both banded and broadcast. Data on yields and P uptake are given in table 14.

Apparently the level of available P in this soil was adequate for good wheat production. Response to applied P was negligible, whereas increases in yield from applied N approached significance. Only about 2 percent of the applied P was utilized by the wheat.

TABLE 14.—*Yield, P derived from fertilizer, and total uptake of native and applied P, by Lemhi wheat, as affected by application of N and P at various rates, Aberdeen, Idaho, 1952* [1]

Fertilizer treatment [2]	P derived from fertilizer	Total P uptake per acre		Yield per acre	
		Soil	Fertilizer	Grain	Straw
	Percent	*Pounds*	*Pounds*	*Bushels*	*Pounds*
No N:					
No P (control)		7. 8		38. 4	2, 332
P (17.5 pounds per acre)	6. 79	9. 9	0. 44	46. 6	2, 644
P (35 pounds per acre)	8. 31	8. 7	. 46	44. 0	2, 612
N (80 pounds per acre):					
No P		10. 3		51. 8	3, 297
P (17.5 pounds per acre)[3]	5. 28	9. 7	. 34	44. 0	2, 737
P (35 pounds per acre)	12. 31	10. 1	. 75	52. 4	3, 359
Least significant difference:					
At 5-percent level	2. 25	N. S.	. 22	13. 5	715
At 1-percent level	3. 11		. 30		964

[1] As reported by Jordon.
[2] See text for details on methods of applying fertilizers.
[3] 2 plots affected seriously by shortage of moisture.

Addition of N tended to increase P uptake from fertilizer applied at the higher rate and to decrease P uptake from fertilizer applied at the lower rate. Addition of N appears to have increased P uptake from fertilizer relatively more than from native P. This apparent N–P interaction may have been caused by one or more of the following reasons: (1) Formation of a more extensive root system with N, thus enabling a more thorough foraging of the soil, particularly in the zone containing applied N and P; (2) increased P uptake as a result of chemical interaction of the N and P compounds in the soil solution, thus increasing availability of P in fertilizer more rapidly than availability of native P; and (3) there may exist in the soil a N/P ratio which functions in a manner not unlike that attributed to the C/N ratio. N–P interactions would represent an adjustment of this ratio.

Wheatgrasses

An experiment was conducted at Aberdeen, Idaho, in 1953 to study the effect of N on P uptake by three wheatgrasses (Siberian, Tall, and Topar) grown in a Declo silt loam. This soil had a pH of 7.7 to 7.9; the CO_2-soluble P ranged from 2.5 to 7 p. p. m.; and the 0.5M $NaHCO_3$-soluble P ranged from 6.5 to 17 p. p. m.

CSP was applied at the rate of 35 pounds of P per acre to all plots; NH_4NO_3 was applied at rates of 0, 80, 120, or 160 pounds of N per acre. Both fertilizers were drilled 4 inches deep. Plants were sampled for radioactivity assay three times during the season. Data for the first two sampling dates (June 6 and July 13) are given in table 15. The radioactivity of the plant samples obtained at the third sampling date was too low to permit reliable readings.

TABLE 15.—*Yields and percentage of P derived from fertilizer by three wheatgrasses, as affected by application of N at various rates, Aberdeen, Idaho, 1953* [1]

Fertilizer treatment [2]	Siberian wheatgrass			Topar wheatgrass			Tall wheatgrass		
	P derived from fertilizer		Yield of seed per acre	P derived from fertilizer		Yield of seed per acre	P derived from fertilizer		Yield of seed per acre
	June 6	July 13		June 6	July 13		June 6	July 13	
	Percent	*Percent*	*Pounds*	*Percent*	*Percent*	*Pounds*	*Percent*	*Percent*	*Pounds*
Control (untreated)			960			760			840
P (35 pounds per acre):									
No N	0. 12	1. 08	800	0. 15	0. 92	627	0. 17	1. 19	946
N (80 pounds per acre)	. 11	2. 77	946	. 24	1. 74	560	. 40	3. 80	1, 186
N (120 pounds per acre)			1, 200			626			1, 280
N (160 pounds per acre)	. 15	2. 69	1, 066	. 40	3. 76	640	. 45	4. 20	1, 253
Least significant difference:									
At 5-percent level	N. S.	1. 19	160	N. S.	. 75	N. S.	N. S.	1. 16	227
At 1-percent level		1. 69	213		1. 07			1. 66	307

[1] As reported by Jordon.
[2] See text for details on methods of applying fertilizer.

TABLE 16.—*Effect of applying N at various rates on yield, uptake of soil and fertilizer P, "A" value, and utilization of applied N, by barley grown in 2 soils in a greenhouse study, Prosser, Wash., 1952* [1]

Soil and rate of N applied	Yield per pot	Total P uptake per pot		"A" value [2]	Utilization of applied N [3]
		Soil	Fertilizer		
Sagemoor fine sandy loam and N at the rate of:	*Grams*	*Milligrams*	*Milligrams*	*Pounds*	*Percent*
15 pounds per acre	4.65	3.86	5.79	25	88
45 pounds per acre	8.64	6.90	8.63	28	50
135 pounds per acre	15.92	7.86	12.36	22	46
Least significant difference:					
At 5-percent level	4.93	1.60	2.49	N. S.	
At 1-percent level	7.08	2.30	3.58		
Ritzville fine sandy loam and N at the rate of:					
15 pounds per acre	5.03	13.88	6.99	70	119
45 pounds per acre	9.11	16.31	9.63	62	62
135 pounds per acre	18.66	19.51	10.54	66	42
Least significant difference:					
At 5-percent level		N. S.	N. S.	N. S.	
At 1-percent level	3.32				

[1] As reported by Hausenbuiller and Weaver. See text for details on fertilizers used and methods of application.
[2] Pounds of P per 2 million pounds of soil.
[3] Percentage of added N recovered.

The soil in these studies supplied adequate P for good growth of all three wheatgrasses. Siberian and Tall wheatgrasses responded significantly to applications of N; Topar did not. Applications of N also increased the percentage of P derived from fertilizer, although the increase was not significant until the second sampling date (July 13). However, as these values increased with time, they might have been appreciably higher at harvesttime had radioassay of the plant material been possible. The initial delay in uptake of P from fertilizer probably can be attributed to its deep placement (4 inches deep).

Greenhouse Studies with Nitrogen

As an integral part of a study of factors important in the determination of "A" values in greenhouse studies, two experiments were conducted at Prosser, Wash., to study the effect of N on the utilization of native and applied P. The first, in 1952, was designed to test the effect of applying N (NH_4NO_3) at various rates on the concurrent uptake of native and applied P and on the resultant "A" values, and to ascertain if stimulation of growth and resultant increased demand for P might cause a more rapid depletion of available native P than of applied P. Thus, one might expect to find the percentage of P from fertilizer in the plant proportional to the rate of N applied. If this were found, increasing the rate of applying N should lower the "A" value for a particular soil.

Two soils were used. One was

a noncalcareous virgin Ritzville fine sandy loam, with a moderate level of available P. The other was a calcareous Sagemoor fine sandy loam with a low level of available P, which had been cropped for a 30-year period without fertilization.

P^{32}-tagged CSP was added at the rate of 35 pounds of P per acre, calculated on a pot-area basis; N was added at rates of 15, 45, and 135 pounds per acre. The fertilizers were mixed with surface soil to a depth of 7 inches in pots. Barley was used as the test crop. Results of this experiment are shown in table 16.

Addition of N increased yields and total P uptake by the plants in both soils. Each increment of added N resulted in approximately proportional increases in P uptake (both native and applied). Consequently, "A" values remained relatively constant throughout the range of N applications. These results suggest that there is an increase in root density and a more thorough exploring of the relatively homogeneous mixture of soil and fertilizer materials with increasing available N.

A second experiment was conducted at Prosser in 1953 to test the effect of three different sources of N (NH_4NO_3, $(NH_4)_2SO_4$, and $NaNO_3$) on "A" values. This experiment was identical in its essential details to the first experiment conducted in 1952. N was applied at the rate of 80 p. p. m.; and P^{32}-tagged resin P was applied at the rate of 35.2 p. p. m. The fertilizers were mixed with surface soil to a depth of 7 inches in pots. Barley was used as the test plant in Sagemoor soil; oats in Ritzville soil. Results of this test are shown in table 17.

TABLE 17.—*Effect of source of N on yield and uptake of soil and fertilizer P, "A" value, and utilization of applied N, by oats and barley grown on different soils in a greenhouse study, Prosser, Wash., 1953* [1]

Crop, soil, and source of N applied [2]	Yield per pot	P uptake per pot		"A" value [3]	Utilization of applied N [4]
		Soil	Fertilizer		
Barley grown in Sagemoor fine sandy loam:	*Grams*	*Milligrams*	*Milligrams*	*Pounds*	*Percent*
NH_4NO_3	5.46	2.14	12.67	14	56.0
$(NH_4)_2SO_4$	5.92	2.27	11.79	16	57.5
$NaNO_3$	5.27	1.97	12.73	12	58.3
Least significant difference: At 5-percent level	N. S.	N. S.	N. S.	N. S.	----------
Oats grown in Ritzville fine sandy loam:					
NH_4NO_3	3.16	16.05	15.67	83	83.0
$(NH_4)_2SO_4$	3.95	20.94	21.37	79	90.3
$NaNO_3$	3.55	16.18	16.94	77	92.1
Least significant difference:					
At 5-percent level	.73	2.93	2.72	N. S.	----------
At 1-percent level	--------	4.44	4.12	--------	----------

[1] As reported by Hausenbuiller and Weaver.
[2] See text for details on methods of applying fertilizers.
[3] Pounds of P per 2 million pounds of soil.
[4] Percentage of applied N recovered.

Experiments by Lorenz and Johnson (*18*) and by Viets and associates (*32*) have shown that the source of N may have a profound effect on uptake of native P by plants. Ammonium sources appear to be more effective than nitrate sources in some instances. This can be attributed, in part, to an increased solubility of phosphate minerals caused by acidulation of ammonium fertilizers.

Addition of $(NH_4)_2SO_4$ resulted in a significant increase in P uptake (both native and applied) in the lime-free Ritzville soil. In the calcareous Sagemoor soil, however, P uptake was similar for all three sources of N. If the effect of $(NH_4)_2SO_4$ is the result of acidulation, it may be assumed that this effect was nullified through neutralization by $CaCO_3$ in the Sagemoor soil. The source of N had little effect on "A" values in the two soils studied.

DISCUSSION

Both greenhouse and field experiments emphasize the importance of applied N on stimulation of root growth and P uptake. In closed systems, represented by potted soils in the greenhouse studies, stimulation resulted in greater root density and more thorough foraging of a relatively homogeneous mixture of native and applied P. Regardless of the concentration of roots within the soil mass, the ratio of P absorbed from the two sources (native and applied) remained relatively constant. Different N carriers may result in different root densities or affect the solubility of P differently. However, when native and applied P are intimately mixed in the soil, any differences that result because of the source of N will affect both native and applied P to a similar extent when they are intimately mixed in the soil.

In the field, application of N may have results markedly different from those observed in the greenhouse. As shown in the wheat and wheatgrass studies, application of N increased the percentage of P obtained from fertilizer. Whether this is the result of increased root density in the vicinity of the fertilizer band or because of increased solubility of the applied P (as a result of the acidulating effect of NH_4NO_3) is not known.

Results of field studies with sugar beets do not parallel those with wheat and wheatgrasses. Unlike the latter crops, the ratio of P absorbed from fertilizer and from native sources by sugar beets remained constant with applications of N. Methods of applying fertilizer were essentially identical for all the crops studied. Differences in utilization of P may be related to differences in soil moisture, the beets being irrigated more than the wheat and grasses. Conceivably, for the sugar beets there was a more complete removal of N from the zone in which the P was banded. For the wheat and grasses, therefore, there would then be a greater chance of more profuse root development in the surface soil where both N and P fertilizers were concentrated.

SUMMARY

(1) Phosphorus fertilizers are classified into four groups based on water solubility and chemical composition. The first three groups appear to be available to plants in calcareous soils if the surface area exposed to root action is great. These three groups include water-soluble and water-insoluble phosphates. The fourth group, apatite-like minerals, is of very low availability to plants in calcareous soils.

(2) Broadcasting and incorporating P in calcareous soils usually

appears to be equal to or better than applying it in bands. However, superiority of a given method of application depends on factors such as type and age of crop, soil fertility, moisture supply, and time of application.

(3) By limiting root extension and the solubility of P, low levels of soil moisture may favor a greater P uptake from applied fertilizer than from the indigenous P in the soil. This is especially important when the fertilizer is applied in bands.

(4) Loss of applied P in calcareous soils by reversion to unavailable form is not generally regarded as serious.

(5) Under similar conditions of soil and fertilizer, various crops differ in their ability to obtain P from the soil (both indigenous and applied).

(6) In scientific literature, nitrogen fertilizers have been reported to both increase and decrease applied P uptake by crop plants. Two of the experiments reported herein are inconclusive and two show that N fertilizers favor increased uptake of applied P.

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